

An integrated tool to assess the role of new planting in PM₁₀ capture and the human health benefits: a case study in London

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Abstract

The role of vegetation in mitigating the effects of PM₁₀ pollution has been highlighted as one potential benefit of urban greenspace. An integrated modelling approach is presented which utilises air dispersion (ADMS-Urban) and particulate interception (UFORE) to predict the PM₁₀ concentrations both before and after greenspace establishment, using a 10 x 10 km area of East London Green Grid (ELGG) as a case study. The corresponding health benefits, in terms of premature mortality and respiratory hospital admissions, as a result of the reduced exposure of the local population are also modelled. PM₁₀ capture from the scenario comprising 75 % grassland, 20 % sycamore maple (*Acer pseudoplatanus* L.) and 5 % Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) was estimated to be 90.41 t yr⁻¹, equating to 0.009 t ha⁻¹ yr⁻¹ over the whole study area. The human health modelling estimated that 2 deaths and 2 hospital admissions would be averted per year.

Capsule

A combination of models can be used to estimate particulate matter concentrations before and after greenspace establishment and the resulting benefits to human health.

Keywords

Air quality, Green Grid, Urban greenspace, Particulate matter, Health impacts

1 **1. Introduction**

2 Sources of PM₁₀ (particles with a diameter of less than 10×10⁻⁶ m) within urban areas
3 of the UK include road traffic, industry and power production (Dore et al., 2005). Results
4 from numerous longitudinal investigations of human respiratory and other diseases show
5 consistent statistical associations between human exposure to outdoor levels of PM₁₀ and
6 adverse health impacts. Health effects range from alveolar inflammation and respiratory-tract
7 infection (specifically pneumonia) (Pope et al., 1995; Holgate, 1996; QUARG, 1996; Defra,
8 2007a) to acute cardiovascular disorders (Pope et al., 1995; Klemm et al., 2000; USEPA,
9 2004). These often lead to substantially increased morbidity and mortality, in particular
10 among elderly individuals (Zelikoff et al., 2003). The adverse health effects of high ambient
11 PM₁₀ concentrations have resulted in the introduction of air quality standards which are
12 designed to be protective of human health. When considered in an economic context, the
13 health costs incurred by PM₁₀ pollution in the UK have been estimated to range between £9.1
14 and 21.4 billion per annum (Defra, 2007a).

15 Although PM₁₀ emissions in the UK have reduced in the last 30 years (Dore et al.,
16 2005; Defra, 2007a), this trend is flattening or reversing in some major urban areas and along
17 roads (Defra, 2007a). A range of measures have been introduced in an attempt to further
18 reduce PM₁₀ emissions, for example tightening of vehicle emissions standards and road
19 pricing initiatives. However, a range of cost-effective abatement measures must be initiated if
20 improvements in air quality are to be any more substantial (Defra, 2007a). Tree establishment
21 in urban areas has been proposed as one measure to reduce ambient PM₁₀ concentrations
22 (Bealey et al., 2007; Nowak et al., 2006, McDonald et al., 2007). PM₁₀ deposition to
23 vegetation has been the subject of a number of recent investigations (Beckett et al., 1998;
24 Gupta et al., 2004; Dammggen et al., 2005; Tiwary et al., 2006). However, the complexities
25 involved in understanding the removal mechanisms for PM₁₀ on different vegetation types,
26 species, planting design and age class has resulted in a large degree of uncertainty regarding
27 the level of reduction that could practically be achieved and how this would relate to human

28 health. This uncertainty is exacerbated by the inherent assumptions and uncertainties in
29 deposition models, where the interception mechanism is influenced by particle size, foliage
30 density, terrain, and meteorological conditions (Ruijgrok et al., 1995; He et al., 2002).

31 Trees can serve as effective sinks for particulates at the canopy level, both via dry,
32 wet and occult deposition mechanisms. For example, work on forest canopies (Peters and
33 Eidan, 1992; Erisman et al., 1997; Freer-Smith et al., 1997; Decker et al., 2000; Urbat et al.,
34 2004) found them to have high capturing efficiencies for airborne particles. The structure of
35 trees and the rough surfaces that they provide increase the incidence of particle impaction and
36 interception by disrupting the flow of air (Beckett et al., 1998), mainly at canopy height
37 (Erisman et al., 1997). It has been suggested that the layered canopy structure of large trees
38 provides a surface area for particulate deposition of between 2 and 12 times that of the area of
39 land they cover (Broadmeadow and Freer-Smith, 1996). Fowler et al. (2004) found that
40 woodlands in the West Midlands, England, collected three times more PM₁₀ than grassland.
41 The differences between tree species play an important role in estimating PM₁₀ capture;
42 leaves with complex shapes, large circumference-to-area ratios, waxy cuticles or fine hairs on
43 their surfaces collect particles more efficiently. Conifers, which are also in leaf all year round,
44 may be more effective than deciduous species (Freer-Smith et al., 2005).

45 Deposition models such as Urban Forest Effects model (UFORE) (Nowak, 1994) and
46 FRAMES (Bealey et al., 2007) are available to assess the potential for particulate matter
47 interception by trees. In UFORE, generic deposition values are assigned to trees due to a lack
48 of empirical deposition data for specific species and for different wind speeds. However,
49 recent reports have shown that tree species and wind speed account for large variations in
50 deposition velocity (Beckett et al., 2000a, 2000b; Freer-Smith et al., 2005). These variations
51 suggest that the use of generic deposition velocities may produce imprecise estimates of PM₁₀
52 flux if they are used to predict deposition where the species composition is different from that
53 for which they have been derived. Recently published deposition velocities measured for

54 specific tree species and wind speeds (Freer-Smith et al., 2004; Freer-Smith et al., 2005)
55 allow more accurate PM₁₀ flux estimations to be produced.

56 The potential use of trees to improve local air quality has been recognised by the UK
57 Government (e.g. Scottish Executive, 2006; Defra, 2007b; Royal Commission on
58 Environmental Pollution, 2007). There is, however, a need for greenspace to be planned and
59 implemented strategically at the landscape level in order to fulfil the potential benefits it can
60 bring to urban environments. These benefits include those to air quality, climate amelioration,
61 sustainable urban drainage, health and well-being. This study aims to estimate the potential
62 for a greenspace initiative to reduce PM₁₀ levels in an area of East London and the
63 corresponding human health impacts on mortality and morbidity. It also aims to demonstrate
64 how this type of integrated modelling approach, comprising environmental and health models,
65 can be used as a tool by practitioners wishing to target greenspace development to areas
66 where air quality is of concern.

67 **2. Materials and methods**

68 *2.1. Study area*

69 The East London Green Grid (ELGG; Figure 1) (Greater London Authority, 2008) is
70 the delivery mechanism of the ‘Greening the Gateway’ initiative in London. It is a proposed
71 *‘network of interlinked, multi-purpose and high quality open spaces that connect areas where*
72 *people live and work with town centres, public transport, the countryside in the urban fringe*
73 *and the River Thames’* that will be created from both new and existing greenspace (Greater
74 London Authority, 2006). The drivers behind the ELGG development are multi-faceted and,
75 whilst PM₁₀ reduction is not a primary driver the improvement of local air quality is seen as a
76 potential benefit of the scheme (Greater London Authority, 2006).

77 This study used a 10 x 10 km region (Figure 2; National Grid Reference TQ 401801,
78 51°30’N, 0°01’E) of the ELGG covering the London Boroughs of Newham and Greenwich.
79 The ELGG within this area occupies 547 ha (5.5 % of the total study area).

80 *2.2. Overview of the integrated approach*

81 The study area falls within a heavily urbanised region of the ELGG, characterised by
82 heavy traffic, industrial activity and London City airport. Sources of PM₁₀ from the whole of
83 Greater London were modelled using ADMS-Urban (version 2.2, Cambridge Environmental
84 Research Consultants, UK; CERC, 2006) to calculate hourly PM₁₀ concentrations at 1.5 m
85 height (human receptor level) for the 10,000 ha study area; a map of average PM₁₀
86 concentrations was then produced. This process used emissions data from the London
87 Atmospheric Emissions Inventory GLA (2006) and meteorological data for 2004 from
88 Heathrow Airport, UK (Meteorological Office, 2006). ADMS-Urban allows a maximum of
89 10,000 output points in the calculation of spatial concentrations; these can be specified using
90 a mix of regular output grid points and additional receptor points. For the presented study the
91 grid resolution for the 10 km x 10 km study area was chosen as a mix of points on a 40 x 40
92 grid (0.25 x 0.25 m) and 18 specified receptor locations. The latter were used to sample the
93 input upstream concentrations in order to calculate the potential flux from vegetation
94 intervention.

95 A canopy PM₁₀-uptake model based on UFORE (Nowak, 1994) was then used to
96 estimate the PM₁₀ interception by the proposed ELGG within the study area. However, the
97 ELGG does not yet have specific information available on the composition of the
98 greenspaces, e.g. species choice, percentage tree cover or planting design. Therefore, a range
99 of possible planting options for these greenspaces was modelled. The ‘most realistic scenario’
100 of PM₁₀ interception by the ELGG within the study area was then used to reproduce the PM₁₀
101 concentration map for the area for use in the human health modelling. This scenario was
102 thought to be most realistic based on social considerations for urban greenspace design, where
103 broadleaves, a range of habitats and areas of open space tend to be preferred by local
104 communities (Lee, 2001). The interception of PM₁₀ by the other scenarios is presented in
105 order to demonstrate the importance of species selection if air quality improvement is an
106 objective of greenspace design and the beneficial role of tree cover versus grassland.

107 The PM₁₀ concentrations post-implementation of the ELGG were estimated in
108 ADMS-Urban using two modifications to the pre-implementation scenario. Firstly, the source
109 strength of each grid cell was adjusted by accounting for the modelled flux to vegetation
110 using the GIS information on the presence of the corresponding vegetation in each grid cell.
111 Secondly, the surface roughness (in metres) was altered to take account of changes to this
112 parameter following greenspace establishment. ADMS-Urban parameterises the boundary
113 layer structure based on the Monin-Obukhov length and the boundary layer height. Using the
114 hourly sequential meteorological data a pre-processor code makes accurate estimation of the
115 boundary layer height for each hour, based on the previous history.

116 The impact of the ELGG on human health from PM₁₀ exposure was compared with a
117 situation of no greenspace establishment. Two models were used to estimate the premature
118 mortality and respiratory hospital admissions, as a result of PM₁₀ exposure, of the populations
119 within the London Boroughs of Newham and Greenwich.

120 *2.3. The potential impact of the ELGG on PM₁₀ concentration*

121 Five scenarios were used to estimate the potential for PM₁₀ interception by the
122 ELGG. These were based on the premise that trees have a greater capacity for PM₁₀ reduction
123 than grassland and that conifers have a greater capacity than broadleaves. Data for sycamore
124 maple (*Acer pseudoplatanus* L.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) were
125 selected to provide the 'best' and 'worst' case scenarios for PM₁₀ interception by tree cover.
126 *A. pseudoplatanus* produces very low deposition velocities due to its low particle capture
127 efficiency and *P. menziesii* exhibits very high deposition velocities (Freer-Smith et al., 2004;
128 Freer-Smith et al., 2005). The five scenarios used, based on a total land area of 547 ha, in the
129 study were:

- 130 1. 100 % grassland;
- 131 2. 50 % grassland, 50 % *A. pseudoplatanus*;
- 132 3. 100 % *A. pseudoplatanus*;

133 4. 75 % grassland, 20 % *A. pseudoplatanus*, 5 % *P. menziesii*;

134 5. 100 % *P. menziesii*.

135 The PM₁₀ flux (F ; in $\text{g m}^{-2}\text{s}^{-1}$) to each greenspace scenario is calculated as the product
136 of the deposition velocity (V_d ; in m s^{-1}) and the pollutant concentration (C ; in g m^{-3}) according
137 to the methodology outlined in Nowak (1994):

$$138 \quad F = V_d \cdot C \quad (1)$$

139 Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-
140 laminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi et al., 1987):

$$141 \quad V_d = (R_a + R_b + R_c)^{-1} \quad (2)$$

142 Hourly meteorological data were used to estimate R_a and R_b . The aerodynamic resistance is
143 calculated as (Killus et al., 1984):

$$144 \quad R_a = u(z) u_*^{-2} \quad (3)$$

145 where $u(z)$ is the mean windspeed at height z (m s^{-1}) and u_* is the friction velocity (m s^{-1}).

$$146 \quad u_* = (k \cdot u(z-d)) [\ln((z-d)/z_o) - \psi_m((z-d)/L) + \psi_m(z_o/L)]^{-1} \quad (4)$$

147 where k = von Karman constant, d = displacement height (m), z_o = roughness length (m), ψ_M
148 = stability function for momentum, and L = Monin-Obukhov stability length. L was estimated
149 by classifying hourly local meteorological data into stability classes using Pasquill's (1961)
150 stability classification scheme and then estimating $1/L$ as a function of stability class and z_o
151 (Golder, 1972). When $L < 0$ (unstable) (Van Ulden and Holtslag, 1985):

$$152 \quad \psi_m = 2 \ln[(1+X)/2] + \ln[(1+X^2)/2] - 2 \tan^{-1}(X) + \pi/2 \quad (5)$$

153 where $X = (1 - 28 z L^{-1})^{0.25}$ (Dyer and Bradley, 1982). When $L > 0$ (stable conditions) (Van
154 Ulden and Holtslag, 1985):

$$155 \quad \psi_m = -17(1 - \exp(-0.29(z-d)/L)) \quad (6)$$

156 The quasi-laminar boundary-layer resistance was estimated as:

$$157 \quad R_b = B^{-1} u_*^{-1} \quad (7)$$

158 where $B^{-1} = 2(2u_*)^{-1/3}$ (Killus et al., 1984).

159 Hourly canopy resistance (R_c) values were derived from yearly-averaged R_a and R_b and
160 deposition velocity values for each tree species ($V_{g(s)}$; in $m\ s^{-1}$):

$$161 \quad R_c = \frac{1}{V_{g(s)}} - (\bar{R}_a + \bar{R}_b) \quad (8)$$

162 $V_{g(s)}$ ($m\ s^{-1}$) values were species-specific (either $V_{g(A.pseudoplatanus)}$ or $V_{g(P.menziesii)}$) and calculated
163 using known relationships between wind speed and $V_{g(s)}$ (using the data from Freer-Smith et
164 al., 2004):

$$165 \quad V_{g(A.pseudoplatanus)} = 0.00119(1.164^u) \quad (\text{number of observations}=9; p<0.001; R^2=0.68) \quad (9)$$

$$166 \quad V_{g(P.menziesii)} = 0.00297(1.404^u) \quad (\text{number of observations}=9; p=0.007; R^2=0.45) \quad (10)$$

167 where $V_{g(A.pseudoplatanus)}$ is the deposition velocity for *A. pseudoplatanus*, $V_{g(P.menziesii)}$ is the
168 deposition velocity for *P. menziesii* and u is windspeed.

169 Deposition velocities for grassland were calculated using measured relationships
170 between deposition velocities for long grass and Pasquill's atmospheric stability classes
171 (Vong et al., 2004).

172 The in-leaf period for *A. pseudoplatanus* was assumed to be 15th May to 1st
173 November. The canopy height used for both species was 10 m and the leaf area indices (LAI)
174 were assumed to be constant throughout the in leaf period at $9.0\ m^2\ m^{-2}$ for *P. menziesii* and
175 $7.0\ m^2\ m^{-2}$ for *A. pseudoplatanus*. The PM_{10} flux (in $g\ m^{-2}\ s^{-1}$) from Equation 1 was used
176 together with the area of each greenspace (in ha) and the LAI of the grass, *A. pseudoplatanus*
177 and *P. menziesii* (multiplied by 2 to account for deposition to both sides of the leaf) to
178 calculate the total annual PM_{10} flux to greenspace (in $t\ ha^{-1}\ yr^{-1}$). Flux data were then used to

179 modify the ADMS-Urban outputs, taking into account the orientation of the greenspace
180 relative to wind direction, in order to estimate the PM₁₀ concentrations across the study area
181 following implementation of the ELGG.

182 *2.4. Assessment of health benefits to the local population*

183 The estimates of the health benefits of the reduction in PM₁₀ concentration are based
184 on exposure-response relationships obtained from time-series epidemiological analyses of
185 daily mortality and respiratory hospital admissions with daily mean PM₁₀ concentration. The
186 exposure-response relationships quantify the short-term (i.e. acute) health effects of exposure
187 due to changes in PM₁₀ concentrations. Epidemiological studies have shown that premature
188 mortality and respiratory hospital admissions risks are positively and linearly associated with
189 exposure to PM₁₀ (COMEAP, 1998; Atkinson et al., 1999; Brunekreef and Holgate, 2002;
190 Medina et al., 2004). The linear coefficients of the inferred regression lines are used to
191 quantify the changes in the risks of health events associated with changes in the pollutant
192 concentration.

193 The two equations below were used to quantify the annual reduction in mortality
194 (ΔM) and hospital admissions (ΔH) due to reduction in PM₁₀ concentration in each of the
195 affected wards in East London:

$$196 \quad \Delta M_i = \alpha \times \Delta C_i \times P_i \times M_0 \quad (11)$$

$$197 \quad \Delta H_i = \beta \times \Delta C_i \times P_i \times H_0 \quad (12)$$

198 where α and β are respectively the regression coefficients of the PM₁₀ exposure-mortality and
199 PM₁₀ exposure-hospital admission relationships ($\alpha=0.00075$ and $\beta=0.00080$), ΔC_i is the
200 modelled reduction in PM₁₀ concentration in ward i ($\mu\text{g m}^{-3}$), P_i is the size of the population
201 of ward i , M_0 and H_0 are respectively the annual baseline mortality (720 per 100,000 of the
202 population) and hospital admission rates (651 per 100,000 of the population) for the overall
203 affected area.

204 The total health benefits are obtained by summing the health benefits over all the wards

$$205 \quad \Delta\hat{M} = \sum_{i=1}^n \Delta M_i \quad (13)$$

$$206 \quad \Delta\hat{H} = \sum_{i=1}^n \Delta H_i \quad (14)$$

207 where n is the total number of affected wards, $\Delta\hat{M}$ and $\Delta\hat{H}$ are respectively the total number
208 of deaths and hospital admissions averted per year across all wards as result of the
209 intervention.

210 The PM₁₀-mortality coefficient was taken from COMEAP (1998) and the PM₁₀-
211 hospital admission coefficient was taken from Atkinson et al. (1999). Population data were
212 obtained from the 2001 Census, annual baseline mortality data from the UK Office of
213 National Statistics and annual baseline respiratory hospital admissions from the UK Hospital
214 Episodes Statistics.

215 **3. Results**

216 *3.1. Potential impact of the ELGG on PM₁₀ concentration*

217 The results of the PM₁₀ interception modelling are shown in Figure 3. *P. menziesii*,
218 due to its greater V_g and LAI values, has a significantly greater capacity to intercept
219 particulates from the atmosphere than *A. pseudoplatanus*; *A. pseudoplatanus* appears only
220 slightly more effective than grass (12.45 t yr⁻¹ removed compared to 3.75 t yr⁻¹ at the Lower
221 Lea Valley as opposed to 258.75 t yr⁻¹ using *P. menziesii*). This represents a four-fold increase
222 when trees are included in urban greenspace design; equating to a removal rate of 0.12 t ha⁻¹
223 yr⁻¹. The amount of PM₁₀ interception is directly proportional to the area of the greenspace;
224 therefore the differences in reductions between greenspaces shown in Figure 3 are a factor of
225 the areas of the greenspaces. The PM₁₀ reductions for the whole ELGG within the study area
226 are 17.99 t yr⁻¹ (0.03 t ha⁻¹ yr⁻¹) under 100 % grassland, 60.49 t yr⁻¹ (0.11 t ha⁻¹ yr⁻¹) under 100
227 % *A. pseudoplatanus*, 1277.13 t yr⁻¹ (2.33 t ha⁻¹ yr⁻¹) under 100 % *P. menziesii*.

228 When the more realistic planting scenario of 75 % grassland, 20 % *A. pseudoplatanus*
229 and 5 % *P. menziesii* (scenario 4) is used the PM₁₀ removal is 90.41 t yr⁻¹ (0.17 t ha yr⁻¹;
230 Figure 4). Figure 5 shows the spatial distribution of PM₁₀ concentrations both before and after
231 implementation of this scenario within the ELGG study area.

232 *3.2. Results from health modelling*

233 The health modelling estimated that 2 premature deaths and 2 respiratory hospital
234 admissions are averted per year due to the implementation of scenario 4 within the ELGG
235 study area.

236 **4. Discussion**

237 *4.1. Potential impact of the ELGG on PM₁₀ concentration*

238 This study suggests that the contribution greenspace makes to improving local air
239 quality is dependant on the percentage cover of trees and their species. The rates of PM₁₀
240 removal for scenario 4 are greater than those found by Nowak (1994) for Chicago who
241 calculated that trees within the city could reduce PM₁₀ concentrations by 0.004 t ha⁻¹ yr⁻¹. The
242 Nowak (1994) study had a lower tree cover at 11% which would, in part, explain the lower
243 rate of PM₁₀ removal. The current study also included the deposition to grassland, which was
244 not taken into consideration in the Chicago study. In addition, the deposition velocities used
245 by Nowak (1994) were smaller than those used for the ELGG as a result of the different
246 species composition; 90% broadleaves and only 10% conifers, and because the re-suspension
247 of particles from trees was assumed to be 50%. Particles deposited onto tree surfaces may
248 remain there, be re-suspended to the atmosphere by wind or be washed off during
249 precipitation events (Nowak, 1994). However, re-suspension of silica particles from an
250 experimental spruce canopy, at a comparable wind speed to that in London, was found to be
251 extremely small at approximately 1% per day of the deposited material (Ould-Dada and
252 Baghini, 2001), for this reason re-suspension was not considered in the current study. Yang et
253 al. (2005), using the UFORE model, found that trees in Beijing removed approximately 0.025

254 t ha⁻¹ yr⁻¹; this greater value can probably be explained by the differences in climate, tree
255 cover (16.4%) and initial PM₁₀ concentrations in Beijing compared to Chicago.

256 It is unsurprising that such studies have predicted relatively similar rates of PM₁₀
257 removal since they all use similar methodologies, models and literature data so the inherent
258 assumptions and therefore uncertainties will be broadly equivalent. However, Broadmeadow
259 et al. (1998) calculated the annual deposition to a *Quercus spp.* woodland located alongside
260 the M6 (West Midlands, England) from leaf collections and measurements of LAI and found
261 that at the end of the growing season the PM₁₀ deposition rate was 0.009 t ha⁻¹ yr⁻¹, suggesting
262 that the models used in these studies are reasonably reliable.

263 This study assumes a canopy height of 10 m; this is likely to represent *A.*
264 *pseudoplatanus* and *P. menziesii* trees of 13-15 and 14-16 years respectively (Edwards and
265 Christie, 1981). The ability of trees to intercept PM₁₀ will vary during the lifetime of the tree;
266 larger trees are capable of removing more PM₁₀ (Nowak, 1994), although younger, smaller
267 trees are surprisingly effective due to their greater foliage densities (Beckett et al., 2000c).
268 Street trees and the edge effect of woodland blocks was also not considered in the study, both
269 of which have been reported to play a significant role in the removal of particles from the air
270 (Hasselrot and Greenfelt, 1987; Neal et al., 1994; Nowak, 1994).

271 The UFORE model has a number of assumptions, some of which could be addressed
272 by the use of a more complex deposition model. This would, however, probably result in a
273 model which was more dependant on site- or regional-specific data which would be more
274 complicated to run and interpret. The assumptions can be summarised in the following
275 paragraphs.

276 The UFORE model only considers dry deposition to greenspace; it does not take into
277 account occult or wet deposition and is therefore likely to underestimate the total deposition
278 (Graustein and Turekian, 1989). However, in this study it is unlikely to make a significant
279 contribution, as the site is not frequently immersed in cloud (Graustein and Turekian, 1989;

280 Broadmeadow and Freer-Smith, 1996) and wet deposition is not affected by the surface
281 roughness of the system so is identical between vegetation types (Fowler et al., 2004).

282 UFORE uses canopy resistance values (R_c) calculated from the average deposition
283 values measured in a field in Chicago minus the R_a and R_b values (Nowak, 1994). These were
284 unlikely to represent the situation in London, therefore the present used species- and wind
285 speed-specific V_g values calculated from relationships developed from the raw data from
286 Freer-Smith et al. (2004) for *A. pseudoplatanus* and *P. menziesii*. This study measured
287 deposition velocity in wind tunnel experiments and so V_g values may not be representative of
288 field conditions, although a range of wind speeds were used.

289 Deposition to *A. pseudoplatanus* was assumed to only occur during the in leaf period,
290 but there will, be some uptake onto woody surfaces during the winter. Nowak (1994)
291 calculated that removal ranged from 0.007 to 0.06 t ha⁻¹ yr⁻¹ between out of leaf and in leaf
292 seasons presumably due to the impact of leaf senescence. LAI was assumed to be constant
293 throughout the year; this will however vary within the growing season (Broadmeadow and
294 Freer-Smith, 1996).

295 4.2. Health impacts of reductions in PM_{10} concentration

296 In the present study, the estimated health benefits are small, with between 2
297 premature deaths and 2 respiratory hospital admissions being averted per year. Powe and
298 Willis (2004) estimated that the existing forest cover within the UK would result in a
299 reduction of 5 to 7 deaths and 4 to 6 respiratory hospital admissions per year due to reductions
300 in PM_{10} and SO_2 pollution. To put the above health benefits in perspective; a recent study on
301 urban air quality management in the UK predicted that by reducing PM_{10} levels in
302 Westminster (Central London) from 1996-1998 roadside levels to achieve an annual mean
303 PM_{10} (gravimetric) target of 20 $\mu\text{g m}^{-3}$, an estimated 8-20 premature deaths would be averted
304 in that area due to reduced short-term exposure and up to 100 deaths from long-term exposure
305 (Mindell and Joffe, 2004).

306 There are also a number of uncertainties associated with the health impacts
307 modelling. The relative risk coefficients used in the mortality calculations are subject to
308 uncertainty. The model did not estimate the difference in respiratory symptoms between pre-
309 and post-intervention. These symptoms would not require hospital admissions but would need
310 medical attention. Changes in respiratory symptoms that need medical attention could be
311 associated with changes in general practice (GP) consultations. There is epidemiological
312 evidence to support the assumption that changes in air pollution impact on GP consultations
313 (e.g. Wong et al., 2002). A recent study, which looked at asthma prevalence in 4-5 year old
314 children in New York found that the presence of street trees was associated with a 29%
315 reduction in early childhood asthma (Lovasi et al., 2008). Although, the authors stated that
316 ‘this study does not permit inference that trees are causally related to asthma at the individual
317 level’. The model also did not consider secondary health impacts which would be relevant if it
318 is assumed that the implementation of the ELGG is likely to have other indirect health effects,
319 for example though recreation, sports, increased use of pedestrian and cycle transport and
320 increase well-being (O’Brien, 2005). There are epidemiological studies which could be used
321 to quantify the health benefits from additional exercise (e.g. Tully et al., 2007).

322 4.3. *Practical considerations for greenspace establishment*

323 The aim of this study was to demonstrate how an integrated tool used be used to
324 predict the impact of greenspace initiative in terms of PM₁₀ concentrations. Modern
325 greenspace aims to be multifunctional and as such must be designed to meet a number of
326 objectives. Considering the wide range of drivers for the ELGG development, of which air
327 quality improvements are only a small part, the relevant proportion of the greenspace taken up
328 by trees is likely to be relatively low. The planting scenario selected for the health impact
329 work demonstrates the value in planting a relatively small proportion of conifer species,
330 which could also be targeted around ‘hot-spots’ of PM₁₀ pollution in order to realise the
331 maximum benefit.

332 Apart from their ability to mitigate PM₁₀, there are many other benefits to tree
333 establishment that have not been considered in this study. These include additional
334 improvements in air quality, for example through the uptake of O₃, SO₂ and NO_x
335 (Broadmeadow and Freer-Smith, 1996). There are also many environmental and social
336 benefits to greenspace creation in general, including their contribution to sustainable urban
337 drainage, soil stabilisation, flood mitigation, shade provision, biodiversity, education,
338 community cohesion and health and well-being. The benefits of greenspace must be
339 considered in tandem with the other, potentially detrimental aspects of greenspace and tree
340 establishment, including VOC emissions, which are implicated in the formation of O₃, pollen
341 production, damage to property and maintenance costs.

342 People's behaviour will also have a significant impact on how the reductions in PM₁₀
343 concentrations affect health. The most significant reductions in PM₁₀ concentrations were
344 estimated to be within the greenspaces themselves, suggesting that, in order for their full
345 effects to be realised, the local residents would need to use the greenspaces. The most
346 significant impacts of tree establishment are likely to be during peak traffic densities when
347 vehicular emissions are greatest. These are also likely to be the time periods of greatest
348 exposure to air pollution, for example when people are out of their houses or places of work
349 and travelling to work or school. Encouraging people to walk or cycle through greenspace
350 rather than walking along the side of roads may result in even greater benefits in terms of
351 human exposure, although this will depend on a number of other factors including the
352 perception of crime, ease of access and the attractiveness of the site. Alternatively, street trees
353 could be used to provide localised improvements in air quality along busy roads or pathways.

354 **5. Conclusions**

355 This study demonstrates that tree planting schemes in urban areas such as the ELGG
356 can make a positive contribution to air quality bringing additional benefits to human health.
357 Furthermore, urban greenspace creation has received attention in recent years through the
358 recognition of the social, environmental and economic benefits that it can bring to

359 communities. The integrated modelling approach presented here provides a tool, which in
360 combination with other models (e.g. to quantify climate amelioration, health and well-being),
361 could be used to assess the potential benefit of such initiatives and provide the evidence base
362 for their continuing role within urban environments.

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375 **7. References**

- 376 Air Quality Expert Group (AQEG), 2005. Particulate matter in the United Kingdom. Defra,
377 London.
- 378 Atkinson R.W., Bremner S.A., Anderson H.R., Strachan D.P., Bland J.M., De Leon A.P.,
379 1999. Short-term associations between emergency hospital admissions for respiratory
380 and cardiovascular disease and outdoor air pollution in London. Archives of
381 Environmental Health 54, 398-411.
- 382 Baldocchi, D.D., Hicks, B.B., Camara, P., 1987. A canopy stomatal-resistance model for
383 gaseous deposition to vegetated surfaces. Atmospheric Environment 21, 91-101.

384 Bealey, W.J., McDonald, A.G., Nemitz, R., Donovan, R., Dragosits, U., Duffy, T.R., Fowler,
385 D., 2007. Estimating the reduction of urban PM₁₀ concentrations by trees within an
386 environmental information system for planners. *Journal of Environmental*
387 *Management* 85, 44-58.

388 Beckett, K.P., Freer-Smith, P.H., Taylor, G., 1998. Urban woodlands: their role in reducing
389 the effects of particulate pollution. *Environmental Pollution* 99, 347-360.

390 Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000a. Effective tree species for local air-quality
391 management. *Journal of Arboriculture* 26, 12-19.

392 Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000b. Particulate pollution capture by urban
393 trees: effect of species and windspeed. *Global Change Biology* 6, 995-1003.

394 Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000c. The capture of particulate pollution by
395 trees at five contrasting urban sites. *Arboricultural Journal* 24, 209-230.

396 Broadmeadow, M.S.J., Freer-Smith, P.H., 1996. Urban woodland and the benefits for local air
397 quality. Department of Environment, HMSO, London.

398 Broadmeadow, M.S.J., Beckett, P., Jackson, S., Freer-Smith, P.H. and Taylor, G., 1998. Trees
399 and pollution abatement. *Forest Research Annual Report and Accounts 1997-1998*,
400 The Stationery Office, London.

401 Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. *Lancet* 360, 1233-1242.

402 CERC, 2006. Modelling of current and future concentrations of PM, NO_x and O₃ in London
403 using ADMS-Urban. Report No. FM642, 1 March 2006. Cambridge Environmental
404 Research Centre, Cambridge.

405 COMEAP, 1998. Quantification of the effects of air pollution on health in the United
406 Kingdom. Committee of the Medical Effects of Air Pollutants, Department of Health,
407 The Stationery Office, London.

408 Dammgen, U., Erisman, J.W., Cape, J.N., Grunhage, L., Fowler, D., 2005. Practical
409 considerations for addressing uncertainties in monitoring bulk deposition.
410 Environmental Pollution 134, 535-548.

411 Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. Energy and material
412 flow through the urban ecosystem. Annual Review of Energy and the Environment
413 25, 685-740.

414 Defra, 2007a. The Air Quality Strategy for England, Scotland, Wales and Northern Ireland.
415 Defra, The Stationery Office, London.

416 Defra, 2007b. A Strategy for England's Trees, Woods and Forests. Defra, London.

417 DETR, 1998. Review of the United Kingdom National Air Quality Strategy. A Consultation
418 Document, 98EP0541/A. The Stationery Office, Norwich.

419 Dore, C.J., Watterson, J.D., Murrels, T.P., Passant, N.R., Hobson, M.M., Baggott, S.L.,
420 Thistlethwaite, G., Goodwin, J.W.L., King, K.R., Adams, M., Walker, C., Downes,
421 M.K., Coleman, P.J., Stewart, R.A., Wagner, A., Sturman, J., Conolly, C., Lawrence,
422 H., Cumine, P.R., 2005. UK Emissions of Air Pollutants 1970 to 2003. AEA
423 Technology, National Environmental Technology Centre, UK.

424 Dyer, A.J., Bradley, E.F., 1982. An alternative analysis of flux-gradient relationships at the
425 1976 ITCE. Boundary-Layer Meteorology 22, 3-19.

426 Erisman, J.W., Draaijers, G., Duyzer, J., Hofschreuder, P., Van Leeuwen, N., Römer, F.,
427 Ruijgrok, W., Wyers, P., Gallagher, M., 1997. Particle deposition to forests- summary
428 of results and application. Atmospheric Environment 31, 321-332.

429 Fowler, D., Skiba, U., Nemitz, E., Choubedar, F., Branford, D., Donovan, R., Rowland, P.,
430 2004. Measuring aerosol and heavy metal deposition on urban woodland and grass
431 using inventories of ²¹⁰Pb and metal concentrations in soil. Water, Air and Soil
432 Pollution 4, 483-499.

433 Freer-Smith, P.H., Holloway, S., Goodman, A., 1997. The uptake of particulates by an urban
434 woodland: site description and particulate composition. *Environmental Pollution* 95,
435 27-35.

436 Freer-Smith, P.H., El-Khatib, A.A., Taylor, G., 2004. Capture of particulate pollution by
437 trees: A comparison of species typical of semi-arid areas (*Ficus nitida* and *Eucalyptus*
438 *globulus*) with European and North American species. *Water Air and Soil Pollution*
439 155, 173-187.

440 Freer-Smith, P.H., Beckett, K.P., Taylor, G., 2005. Deposition velocities to *Sorbus aria*, *Acer*
441 *campestre*, *Populus deltoides* X *trichocarpa* 'Beaupre', *Pinus nigra* and X
442 *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban
443 environment. *Environmental Pollution* 133, 157-167.

444 GLA, 2006. London Atmospheric Emissions Inventory 2003. The Environment Group,
445 Greater London Authority, City Hall, London.

446 Golder, D.G., 1972. Relations among the stability parameters in the surface layer. *Boundary-*
447 *Layer Meteorology* 3, 47-58.

448 Graustein, W.C. and Turekian, K.K., 1989. The effects of forests and topography on the
449 deposition of sub-micrometer aerosols measured by lead-210 and cesium-137 in soils.
450 *Agricultural and Forest Meteorology* 47, 199-220.

451 Greater London Authority, 2006. East London Green Grid Primer. Greater London Authority,
452 London.

453 Greater London Authority, 2008. East London Green Grid Framework. London Plan
454 (Consolidated with alterations since 2004). Supplementary Planning Guidance.
455 Greater London Authority, London.

456 Gupta, A., Kumar, R., Maharaj Kumari, K., Srivastava, S.S., 2004. Atmospheric dry
457 deposition to leaf surfaces at a rural site of India. *Chemosphere* 55, 1097-1107.

458 Hanna, S.R., Paine, R., Heinold, D., Kintigh, E. and Baker, D., 2007. Uncertainties in air
459 toxics calculated by the dispersion models AERMOD and ISCST3 in the Houston
460 ship channel area. *Journal of Applied Meteorology and Climatology* 46, 1372-1382.

461 Hasselrot, B., Grennfelt, P. 1987. Deposition of air pollutants in a wind-exposed forest edge.
462 *Water, Air and Soil Pollution* 34, 135-143.

463 He, K., Huo, H., Zhang, Q., 2002. Urban air pollution in China: Current status, characteristics,
464 and progress. *Annual Review of Energy and the Environment* 27, 397-431.

465 Holgate, S., 1996. Air quality and health: Is there an association with asthma? 63rd National
466 Society for Clean Air Environmental Protection Conference and Exhibition, National
467 Society for Clean Air, Brighton.

468 Killus, J., Meyer, J.P., Durran, D.R., Anderson, G.E., Jerskey, T., Reynolds, S.D., Ames, J.,
469 1984. Continued research in mesoscale air pollution simulation modelling. Volume
470 V: Refinements in numerical analysis, transport, chemistry, and pollutant removal.
471 U.S. Environmental Protection Agency, Washington DC, EPA/600/3-84/095a.

472 Klemm, R., Mason Jr, R., Heilig, C., Neas, L., Dockery, D., 2000. Is daily mortality
473 associated specifically with fine particles? Data reconstruction and replication of
474 analyses. *Journal of the Air and Waste Management Association* 50, 1215-1222.

475 Lee, T.R. 2001. Perceptions, attitudes and preferences in forests and woodlands. Forestry
476 Commission Technical Paper 18. Forestry Commission, Edinburgh.

477 Lovasi, G.S., Quinn, J.W., Neckerman, K.M., Perzanowski, M.S., Rundle, A., 2008. Children
478 living in areas with more street trees have lower asthma prevalence. *Journal of*
479 *Epidemiology and Community Health* 62, 647-649.

480 McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan,
481 R.G., Brett, H.E., Hewitt, C.N., Nemitz, E., 2007. Quantifying the effect of urban tree
482 planting on concentrations and depositions of PM₁₀ in two UK conurbations.
483 *Atmospheric Environment* 41, 8455-8467.

484 Medina S., Plasencia A., Ballaster, F., Mucke, H.G., Schwartz, J., 2004. Apheis: Public health
485 impact of PM₁₀ in 19 European cities. *Journal of Epidemiology and Community*
486 *Health* 58, 831-836.

487 Meteorological Office, 2006. Meteorological Office Integrated Data Archive System
488 (MIDAS) Land Surface Stations data (1853-current), [Internet]. British Atmospheric
489 Data Centre. Available from <http://badc.nerc.ac.uk/data/ukmo-midas>.

490 Mindell, J., Joffe, M., 2004. Predicted health impacts of urban air quality management.
491 *Journal of Epidemiology and Community Health* 58, 103-113.

492 Neal, C., Ryland, G.P., Conway, T., Jeffery, H.A., Neal, M, Robson, A.J., Smith, C.J., Walls,
493 J., Bhardwaj, C.L., 1994. Interception of chemicals at a forest edge for a rural low-
494 lying site at Black Wood, Hampshire, Southern England. *The Science of the Total*
495 *Environment* 142, 137-141.

496 Nowak, D. J., 1994. Air pollution removal by Chicago's Urban Forest. In: McPherson, E.G.,
497 Nowak, D.J., Rowntree, R.A. (Eds.). *Chicago's Urban Forest Ecosystem: Results of*
498 *the Chicago Urban Forest Climate Project*. U.S. Department of Agriculture, Forest
499 Service, Northeastern Forest Experiment Station, Radnor, PA, pp. 63-82.

500 Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and
501 shrubs in the United States. *Urban Forestry and Urban Greening* 4, 115-123.

502 O'Brien, E., 2005. *Trees and woodlands - Nature's health service*. Forest Research, Farnham.

503 Ould-Dada, Z., Baghini, N.M., 2001. Resuspension of small particles from tree surfaces.
504 *Atmospheric Environment* 35, 3799-3809.

505 Pasquill, F., 1961. The estimation of the dispersion of windborne material. *Meteorological*
506 *Magazine* 90, 33-49.

507 Peters, K., Eiden, R., 1992. Modelling the dry deposition velocity of aerosol particles to a
508 spruce forest. *Atmospheric Environment* 26, 2555-2564.

509 Pope, C.A.I., Dockery, D.W., Schwartz, J., 1995. Review of epidemiological evidence of
510 health effects of particulate air pollution. *Inhalation Toxicology* 7, 1-18.

511 Powe, N.A., Willis, K.G., 2004. Mortality and morbidity benefits of air pollution (SO₂ and
512 PM₁₀) absorption attributable to woodland in Britain. *Journal of Environmental*
513 *Management* 70, 119-128.

514 QUARG, 1996. Airborne particulate matter in the United Kingdom: Third report of the
515 Quality of Urban Air Review Group. Institute of Public and Environmental Health,
516 University of Birmingham, Birmingham.

517 Royal Commission on Environmental Pollution, 2007. Twenty-sixth Report: The Urban
518 Environment. The Stationery Office, Norwich.

519 Ruijgrok, W., Davidson, C.I., Nicholson, K.W., 1995. Dry deposition of particles:
520 implications and recommendations for mapping of deposition over Europe. *Tellus*
521 47B, 587-601.

522 Scottish Executive, 2006. The Scottish Forestry Strategy. Forestry Commission Scotland,
523 Edinburgh.

524 Tiwary, A., Morvan, H.P., Colls, J.J., 2006. Modelling the size-dependent collection
525 efficiency of hedgerows for ambient aerosols. *Journal of Aerosol Science* 37, 990-
526 1015.

527 Tully, M.A., Cupples, M.E., Hart, N.D., McEneny, J., McGlade, K.J., Chan, W-S., Young,
528 I.S., 2007. Randomised controller trial of home-base walking programmes at and
529 below current recommended levels of exercise in sedentary adults. *Journal of*
530 *Epidemiology and Community Health* 61, 778-783.

531 Ubat, M., Lehndorff, E., Schwark, L., 2004. Biomonitoring of air quality in the Cologne
532 conurbation using pine needles as a passive sampler - Part I: magnetic properties.
533 *Atmospheric Environment* 38, 3781-3792.

- 534 USEPA, 2004. Air quality criteria for particulate matter. U.S. Environmental Protection
535 Agency, Washington, DC, EPA 600/P-99/002aF-bF.
- 536 Van Ulden, A.P., Holtslag, A.A.M., 1985. Estimation of atmospheric boundary-layer
537 parameters for diffusion applications. *Journal of Climate and Applied Meteorology*
538 24, 1196-1207.
- 539 Vong, R.J., Vickers, D., Covert, D.S., 2004. Eddy correlation measurements of aerosol
540 deposition to grass. *Tellus* 56B, 105-117.
- 541 Wong, T.W., Wun, Y.T., Yu, T.S., Wong, C.M., Wong, A.H.S, 2002. Air pollution and
542 general practice consultations for respiratory illnesses. *Journal of Epidemiology and*
543 *Community Health* 56, 949-950.
- 544 Yang, J., McBride, J., Zhou, J., Sun, Z., 2005. The urban forest in Beijing and its role in air
545 pollution reduction. *Urban Forestry and Urban Greening* 3, 65-78.
- 546 Zelikoff, J.T., Chen, L.C., Cohen, M.D., Fang, K., Gordon, T., Li, Y., Nadziejko, C.,
547 Schlesinger, R.B., 2003. Effects of inhaled ambient particulate matter on pulmonary
548 antimicrobial immune system. *Inhalation Toxicology* 15, 131-150.

Fig. 1. Location of the study area within the wider East London Green Grid (the study area is contained within the dotted square) (Greater London Authority, 2006).

Fig. 2. Locations of greenspace within the East London Green Grid included in the assessment of vegetation intervention (Greater London Authority, 2006).

Fig. 3. Potential PM₁₀ flux to different scenarios of planting composition within the study area of the East London Green Grid (Syc=*A. pseudoplatanus*; DF=*P. menziesii*)

Fig. 4. Spatial distribution of the potential reduction in PM₁₀ concentrations following implementation of the 75% grassland, 20% *A. pseudoplatanus* and 5% *P. menziesii* scenario in the East London Green Grid within the study area.

Fig. 5. PM₁₀ concentrations from ADMS-Urban within the study area a) prior to and b) post implementation of the 75% grassland, 20% *A. pseudoplatanus* and 5% *P. menziesii* scenario in the East London Green Grid. [note: the location of the London City Airport runway is shown with a rectangular patch in the upper panel.]

Figure1

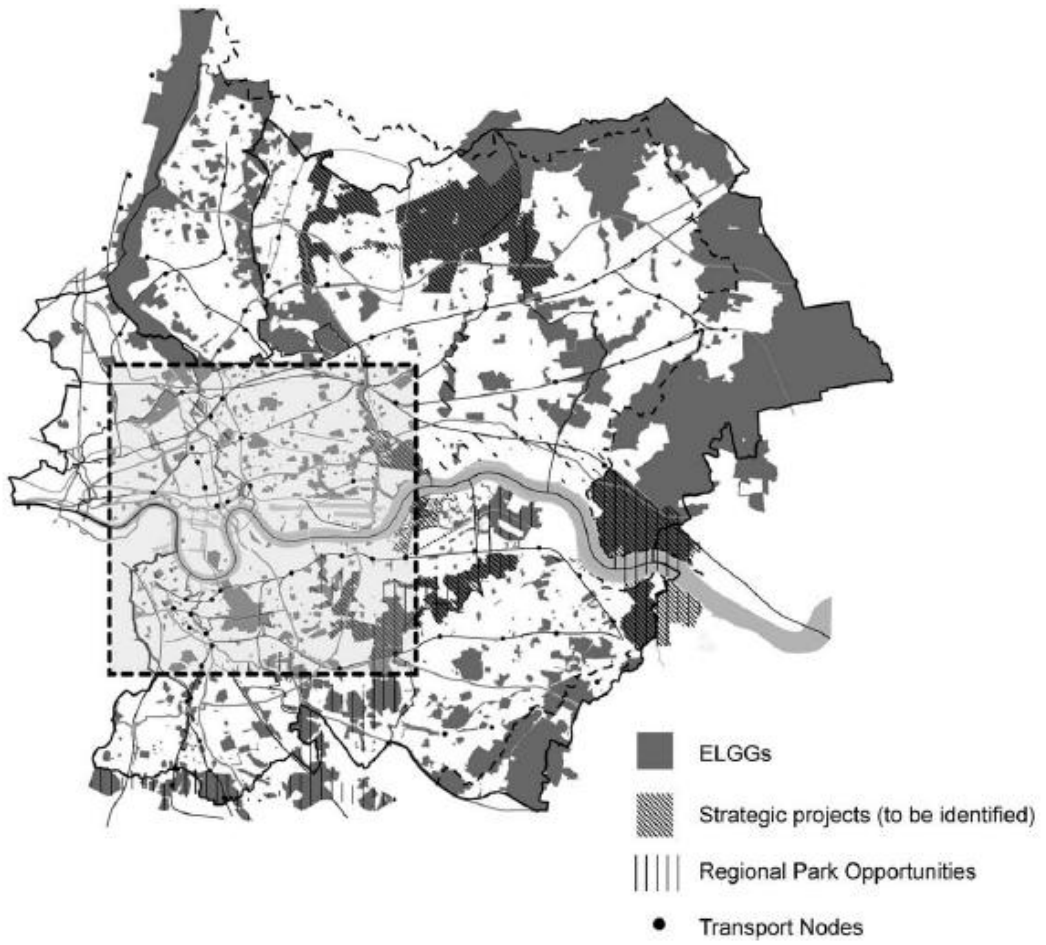


Figure 2

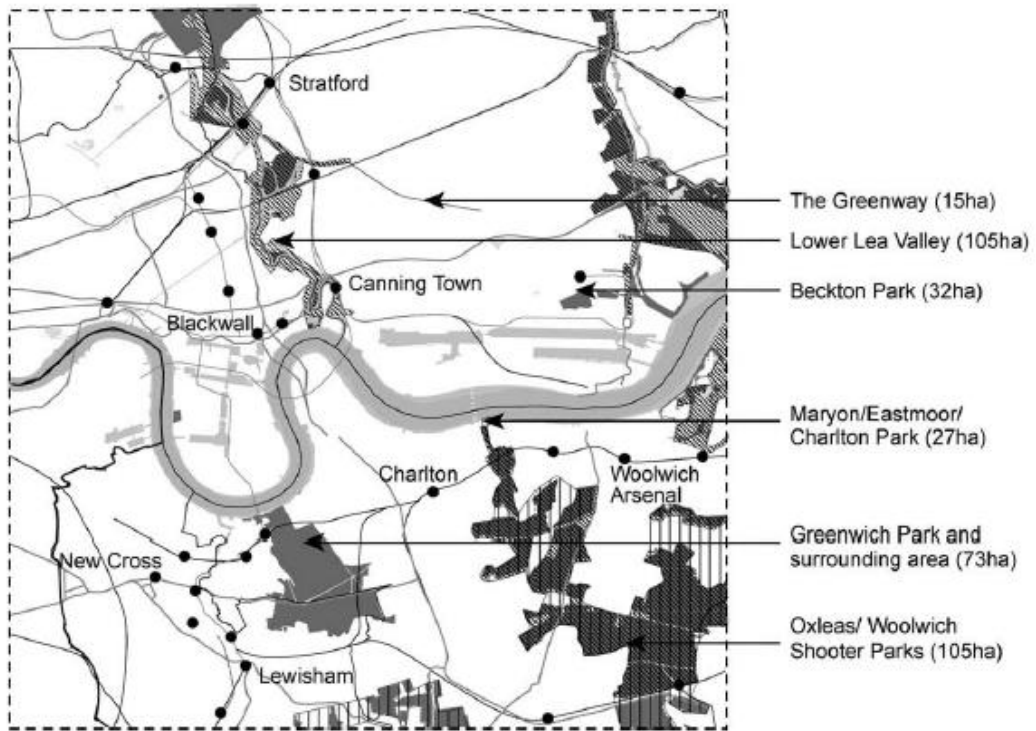


Figure 3

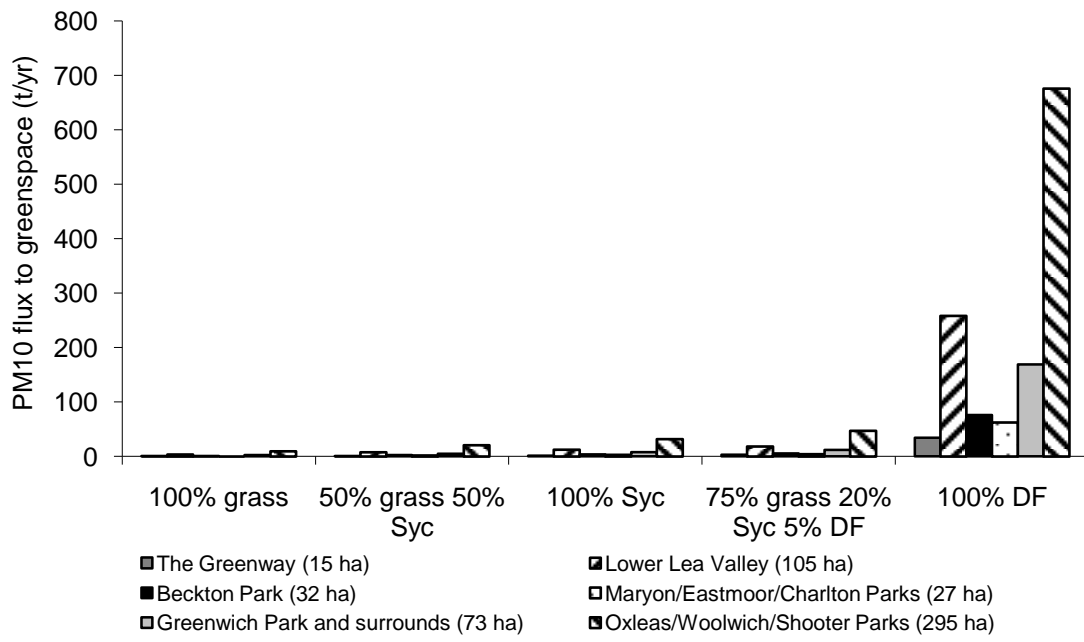


Figure 4

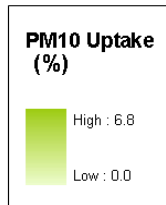


Figure 5

